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Spatial and temporal scales of variability of cyanobacteria harmful algal blooms from NOAA GLERL airborne hyperspectral imagery

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ABSTRACT

NOAA GLERL has routinely flown a hyperspectral imager to detect cyanobacteria harmful algal blooms (cyanoHABs) over the Great Lakes since 2015. Three consecutive years of hyperspectral imagery over the Great Lakes warn drinking water intake managers of the presence of cyanoHABs. Western basin imagery of Lake Erie contributes to a weekly report to the Ohio Environmental Protection Agency using the cyanobacteria index (CI) as an indicator of the presence of cyanoHABs. The CI is also used for the weekly NOAA NCCOS cyanoHAB Lake Erie bulletin applied to satellite data. To date, there has not been a sensor comparison to look at the variability between the satellite and hyperspectral imagery on a pixel-by-pixel basis, as well as a time scale comparison between measurements from buoys and shipboard surveys. The spatial scale is a measure of size of a cyanobacteria bloom on a scale of meters to kilometers. The change in the spatial scale or spatial variability has been quantified from satellite and airborne imagery using a decorrelation scale analysis to find the point at which the values are not changing or are not correlated with each other. The decorrelation scales were also applied to the buoy and shipboard survey data to look at temporal scales or changes in time on hourly to daytime scales for blue-green algae, chlorophyll and temperature. These scales are valuable for ecosystem modelers and for those initiating sampling efforts to optimize sampling plans and to infer a potential mechanism in an observational study from a synoptic viewpoint.

Introduction

The phytoplankton community in the western basin of Lake Erie is typically driven by a combination of physical and chemical processes that are variable over wide-ranging scales of time and space including: wind transport and mixing, climate variability, lake surface temperature fluctuations and phosphorous loading. (Beletsky et al., 2017; Obenour et al., 2014; Paerl and Huisman, 2009; Wynne et al., 2013) The coupling between these physical, chemical and biological parameters is not easily resolved by a single platform, especially in a turbid-shallow water environment such as Lake Erie with rapid fluctuations within hours to days. NOAA's Great Lakes Environmental Research Laboratory (GLERL) in collaboration with the Cooperative Institute for Great Lakes Research (CIGLR) are monitoring recurring cyanoHABS (cyanbacteria Harmful Algal Blooms) with an extensive network of observational equipment deployed to capture the variability of this dynamic system. This network is used to understand the temporal and spatial scales related to cyanoHAB development in order to predict the timing and extent of cyanoHABs in the western basin of Lake Erie. The resulting information products provide awareness of raw water condition to drinking water intake managers in the western basin.

Weekly shipboard sampling provides the vertical coverage of the water column during the cyanoHAB events but does not capture the temporal fluctuations in higher and lower frequencies at a buoy location or spatially from multispectral satellite or airborne hyperspectral imagery. The satellite and hyperspectral synoptic coverage are enhanced on daily time scales with a combination of satellite and hyperspectral remote sensing, where hyperspectral remote sensing adds the spatial (1 m scales) and spectral coverage (100 s of channels/bands for the wavelengths observed, 400–900 nm, 240 bands, 144 bands in the visible spectrum and 96 bands in the infrared range) not observed by satellites (300 to 1 km scales and 30–40 channels or bands). Buoy observations afford the additional temporal coverage that satellite and hyperspectral remote sensing is not able to provide due to fly over limitations and adds the frequency needed to understand what is happening on minute to hourly time scales. The combination of all of these platforms increases the ability to predict the timing of cyanoHABs during the bloom season and to adequately warn stakeholders.

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Monitoring for CyanoHABS has been critical in the Great Lakes as cyanotoxins are potentially released in areas such as Lake Erie, Saginaw Bay and Green Bay. In the Great Lakes the prevalent HABs are composed of cyanobacteria, commonly known as blue-green algae and are typically from the genera *Microcystis (*specifically *Microcystis aeruginosa), Dolichospermum* and *Planktothrix* (Davis et al., 2009, 2015). The HSI (Hyperspectral Imager) has been flown weekly by NOAA GLERL during the past three years, contributed to early warning and detection of CyanoHABs for potential health risks to humans and animals through recreational activities and municipal drinking water. CyanoHABs are a common occurrence in the western basin of Lake Erie and are driven by agricultural runoff in this shallow lake (Bridgeman et al., 2012; Michalak et al., 2013). A phytoplankton bloom is defined not by the level of abundance, but whether it has harmful consequences (Smayda, 1997). The annual occurrence of potentially harmful algal blooms in the western basin of Lake Erie is of greatest concern to municipal water intake facilities.

The CyanoHABs in Lake Erie have spurred many studies in regard to forecasting the timing drivers and peak of the bloom (Budd et al., 2001; Ho and Michalak, 2015; Michalak et al., 2013; Stumpf et al., 2012; Wynne et al., 2013, 2010, 2008; Wynne and Stumpf, 2015). Sampling schemes for the hyperspectral flyovers, shipboard sampling and instrumentation on the buoys are optimally designed to best capture the bloom and physical parameters if the time scales of the phytoplankton response to physical processes are known as well as the spatial variability of these parameters (buoy temperature, winds, blue-green algae and chlorophyll). The goal of this research is to identify the variability and correlation between biological and physical parameters throughout the 2017 field season with buoy, shipboard, satellite and hyperspectral data with a particular focus on NOAA Alliance for Coastal Technologies (ACT) efforts underway on August 16, 2017.

Methods

Study area - western basin of Lake Erie

Lake Erie has experienced episodic cyanoHAB events since the 1960s with resurgence in the 1990s as a possible result of the introduction of the invasive dreissenid mussels which exhibit selective feeding behavior (Budd et al., 2001; Vanderploeg et al., 2001). In the 1970s actions were put in place under the Great Lakes Water Quality Agreement (GLWQA) that resulted in reduced phosphorous loads, the primary driver of the seasonal algal growth, into the lake (Bruce and Higgins, 1978). As a result there was a decrease in bloom events from the 1970s to 1990s after reduction targets were generally met. The return of algal blooms in 1995 was primarily composed of the dominant toxic genus, *Microcystis* and was spurred by an increase in soluble reactive phosphorus from agricultural runoff from the Maumee River as well resuspension of sediment during extreme wind events (Brittain et al., 2000; Vanderploeg et al., 2001). *Microcystis* is a buoyant species known to form large mats of ‘scum’ during calm wind conditions, warmer waters (above 15C) and high light availability (Davis et al., 2009, 2015). Scum events were highly visible in many of the hyperspectral images and were an integral part of the early warning detection system during repetitive weekly flights over the municipal water intake locations. However not all cyanobacteria form surface scums and mapping their distribution is important for stakeholders interested in bloom extent within the western basin of Lake Erie. Flying the Resonon Pika II Hyperspectral imager on a weekly basis has provided the coverage needed to monitor the extent and frequency of cyanoHABS in Lake Erie.

Resonon Pika II hyperspectral imager and manned aircraft flights

In recent decades, remote detection of cyanoHABs has improved with technological advances in the use of airborne hyperspectral imagers (HSI) (Beck et al., 2017; Kudela et al., 2015; Kutser et al., 2001; Lekki et al., 2017, Ortiz et al., 2017) and with the current development of a set of new satellites for hyperspectral detection (HYSPRI and PACE). NOAA GLERL has flown a Resonon HSI for the past three years to monitor cyanoHABs in the Great Lakes along with weekly shipboard sampling and time-series buoy observations (Fig. 1).

The Pika II HSI developed by Resonon has a high signal-to-noise ratio (maximum is 198, pers. comm. with Resonon), and a compact camera that is $3.8 \times 6.6 \times 2.5$ in. The HSI was mounted in a vibration isolation pod that was bolted to a camera port on the underside of a single engine Cessna Centurion along with a GPS/IMU, data acquisition computer, and data storage drive and data readout. The Pika II HSI has 240 spectral bands from 400 to 900 nm and a typical spatial resolution of 1 m depending on the flight altitude. Altitudes that were typically flown over the Great Lakes were between 900 and 1700 m which resulted in a typical swath width of 640 to 2100 m. The data was written to the storage drive approximately every 650 megabytes at a typical swath length of 2100 m and each flight typically collected 350 gigabytes of data. This data was processed with Resonon's proprietary software, called Spectronon from raw to radiance image cubes. The radiance cubes were then georeferenced in IDL based on the pitch, roll and yaw of the aircraft and the GPS location referenced from the aircraft to the location on the earth. These images were written to geotiffs and Google KMZ and KML files for easy dissemination to the user community and within an online web portal. The atmospheric correction and internal sensor correction (de-striping and smile correction) algorithms are currently being tested on this data set. De-striping is a method to remove stripes in the image from variable gains in the sensors/camera retrieval and the smile correction is for push-broom or line-scan cameras that have a ‘frown’ curve in the spectra from the middle to outer edges of the image. For the purpose of the preliminary analysis, an algorithm that ignored the top of the atmosphere effects was applied and solar zenith angle, solar atmospheric radiances and earth-sun distances were not used. Top of atmosphere in this case is the height of the aircraft that the sensor was flown on over Lake Erie.

The manned aircraft flights were flown out of the Ann Arbor from August until November in 2015, May through October during 2016 and May through November in 2017 by Aerodata Associates, Inc. There was a total of eight flights during 2015, 31 during 2016 and 27 during 2017. Weekly flights were conducted over the western basin of Lake Erie and biweekly over Saginaw Bay during each of the three years.

Cyanobacteria index applied to Resonon Pika II hyperspectral imagery

The cyanobacteria index (CI) determines the range from low to high for the abundance of cyanobacteria (blue-green algae. This index has been applied to satellite data in the past for the western Lake Erie HAB Bulletin that has been distributed through NOAA's National Centers for Coastal Ocean Science (NCCOS) twice weekly to forecast the blooms. The CI (Wynne and Stumpf, 2015, Wynne et al., 2013, 2010, 2008) was applied to the Resonon Pika II hyperspectral imagery after converting the images to Rayleigh surface reflectance (rhos) by removing the blue sky effects from the raw radiance values, taking into account that the 681 nm band is readily available with hyperspectral imagery that has 240 spectral bands and not with MODIS bands. The 681 band was the original band used MERIS based CI algorithm. Rayleigh surface reflectance is the reflectance of the surface of the water plus the aerosols above, whereas typically surface reflectance (Rrs) is used in remote sensing with the aerosols removed. The adjusted MODIS CI was used on the MODIS imagery (Wynne and Stumpf, 2015). The CI is a spectral shape algorithm that takes advantage of the reflectance peak in the 709 nm, red range that inherently is not influenced by detrital pigments. Wynne et al. (2008) used this spectral shape algorithm to distinguish cyanobacterial blooms from other algal

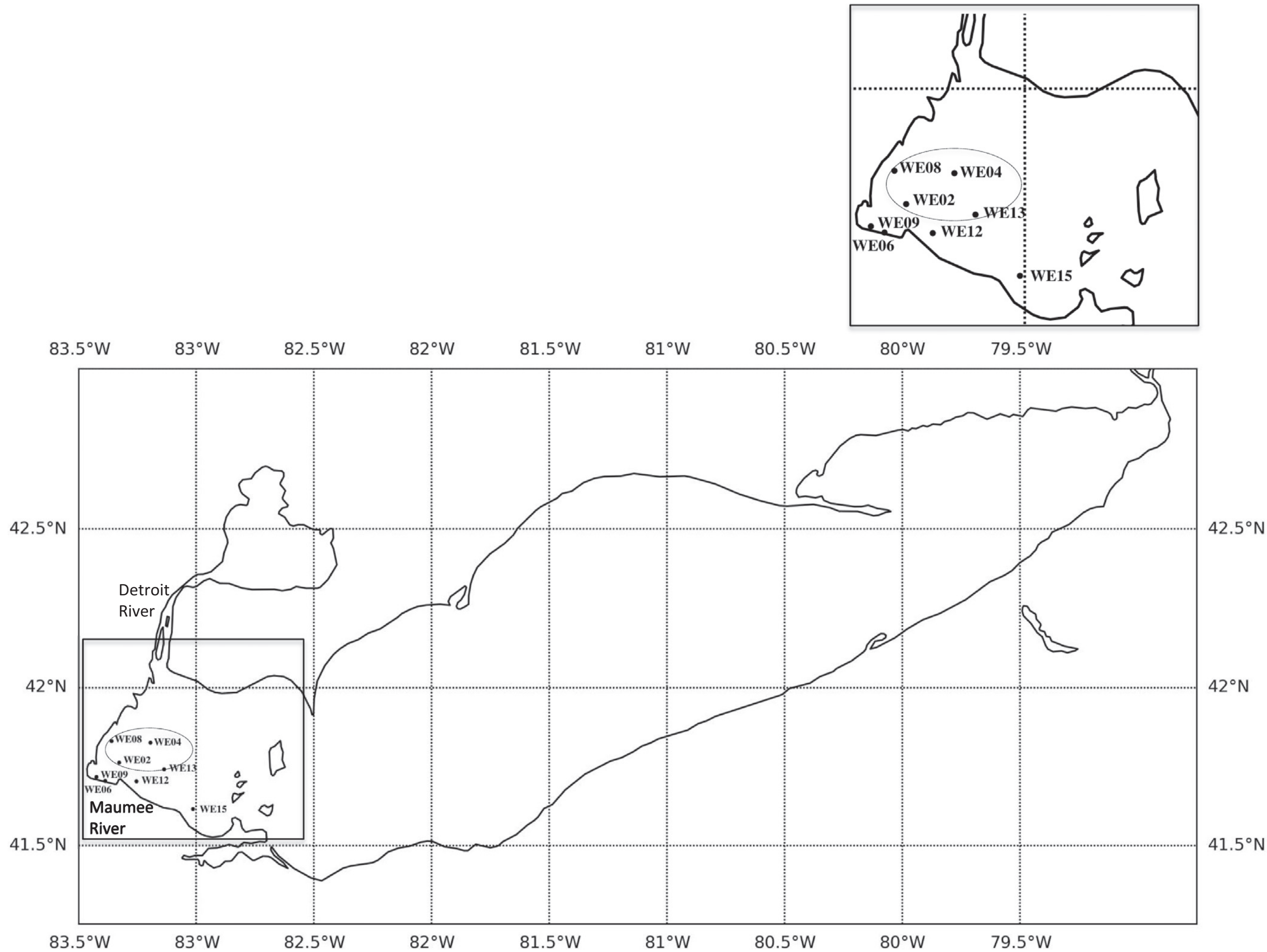

Fig. 1. A map of Lake Erie and the buoy locations and Maumee and Detroit River locations. The dashed circle denotes the buoys analyzed, WE2, WE4 and WE8.

blooms in the western basin of Lake Erie. They calculated the spectral shape as:

$$SS(\lambda) = nLw(\lambda) - nLw(\lambda^-) - \{nLw(\lambda^+) - nLw(\lambda^-)\} \times (\lambda - \lambda^-)/(\lambda^+ - \lambda^-)$$

SS is the spectral shape, nLw is the normalized water leaving radiance, λ is 681 nm, λ + is 709 nm and λ- is 665 nm (Wynne et al., 2008). Cyanobacterial blooms have a negative SS(681) or a sag in the reflectance (Wynne et al., 2008) when normalized water leaving radiance (nLW) falls below the baseline defined as a straight line drawn between 665 nm and 709 nm. A typical reflectance peak occurs at 681 nm but due to the scattering processes of the gas vacuoles of Microcystis, the scattering overwhelms the fluorescence and shifts the peak reflectance to 700–710 nm (Gilerson et al., 2010; Wynne et al., 2008). This peak at 709 nm also has the potential to be influenced by sediment rich waters that reflect in the red portion of the electromagnetic spectrum. For the purposes of warning drinking water intake managers in a timely manner and with a reliable method, the raw radiance values from the Resonon Pika II were used with the same wavelengths as the Wynne et al. (2008) methods since top of atmosphere was not of a concern with lower altitude overflights without the full influence of the column of atmospheric effects found with space-borne sensors. This was also motivated by a desire to compare the weekly HAB bulletin processed CI image with the hyperspectral data to see where the hypersepctral data could fill in the gaps nearshore and underneath clouds. In addition to the modified CI, maps of phytoplankton functional types beyond cyanobacteria are under development to extend to maps of other phytoplankton groups for water intake managers. This will account for the high variability and optical complexity found in Lake Erie and will be reported in future manuscripts.

HAB bulletin contribution with airborne data

NCCOS distributes a twice-weekly HAB bulletin with cyanobacteria bloom extent and intensity, that the western Lake Erie user community relies on to track the bloom development. This is based on available satellite imagery from either the Moderate Resolution Imaging Spectrometer (MODIS) Terra or Aqua sensors or the newly launched, Sentinel-3 Ocean and Land Colour Instrument (OLCI) sensor. The CI is applied to this imagery along with the forecasted position of the bloom using the surface currents from the Great Lakes Coastal Forecasting System (GLCFS). The Great Lakes are inherently cloud covered, even during the summer months, averaging 60–70 cloud free images a year, limiting the coverage to capture cyanoHAB events from satellites. Nearshore regions are also difficult to remotely sense being confounded with strong bottom reflectance signals close to the coast. Hyperspectral imagery has the ability to capture the shorelines in the context of 1 m scales compared to a satellite that resolves the area at 30 m to 1 km. Satellites experience inherent mixed-pixel issues in close proximity to the coast, where the likelihood of this occurrence is less with the spatial scales from hyperspectral imagers. The additional advantage of flying the Resonon Pika II HSI is that the airplane is able to fly under clouds and in those nearshore regions to fill in the gaps in the satellite data with high-resolution airborne imagery. The Resonon Pika II images are typically 1-m resolution depending on flight altitude and objective lens used, whereas the MODIS imagery is 1-km and Sentinel 3 OLCI is 300-meter resolution. The OLCI imagery was compared to the hyperspectral imagery for this analysis. The hyperspectral imagery was not binned up to the OLCI pixel size due to the changing swath direction of the airplane imagery and because one hyperspectral image fits almost precisely into three to four pixels of the OLCI imagery and one pixel of the MODIS imagery. Fig. 2 shows the visual differences in scales of spatial variability between MODIS imagery on the left (1 km spatial resolution) and OLCI satellite imagery on the right (300 m spatial resolution). Both the satellite and hyperspectral imagery have been converted to the cyanobacteria index with recognizable differences in the relative colour scales when going from 1 km down to 1 m spatial resolution in the hyperspectral imagery. It is important to note that the hyperspectral imagery is obtained from top of atmosphere, Rayleigh surface reflectance (rho-s) and the satellite imagery CI is derived from water-leaving radiance values (nLw). Furthermore, the hyperspectral imagery was not binned up to the spatial resolution of the satellite imagery with one hyperspectral image fitting within the size of one pixel of MODIS imagery and will be a focus of future research on the full length of the hyperspectral flight path.

Shipboard and buoy measurements

The Cooperative Institute for Great Lakes Research at the University of Michigan partners with NOAA GLERL to collect shipboard measurements weekly during the spring-summer bloom season in addition to helping to maintain the continuous buoy observations. There are eight weekly sampling stations and continuous observation buoys are located at four of these stations. Some of the weekly measurements include chlorophyll concentration, phytoplankton cell counts, particulate and dissolved microcystin concentrations, extracted phycocyanin and turbidity. For the purposes of this analysis, the phytoplankton cell counts and the microcystin concentrations were compared to the hyperspectral imagery when there was overlap with the sampling data.

Chlorophyll, cyanobacteria, and temperature sensors on buoys

Each of the buoys was equipped with a XYLEM EXO2 sonde with sensors mounted approximately 1 m below the water surface and sampling at 15 min intervals. Sensors on each sonde included depth, temperature, conductivity, pH, dissolved oxygen, turbidity, and fluorometers for chlorophyll-a (Chla), and phycocyanin (bga) and fdom (fluorescence corresponding to dissolved organic matter). Sondes were serviced on an approximately monthly schedule, with pre and post deployment calibration checks performed according to Xylem protocols (e.g. Chla and BGA were checked against Rhodamine WT dilutions).

Sonde data were stored internally and by a connected Campbell Scientific CR1000 data logger, and transmitted at 15-minute intervals to a GLERL server for archiving and near real time web display.

Underway chlorophyll and blue-green algae sensors

Underway sampling was performed on the NOAA GLERL research vessel R4108, a converted 41 ft USCG Utility boat. During underway

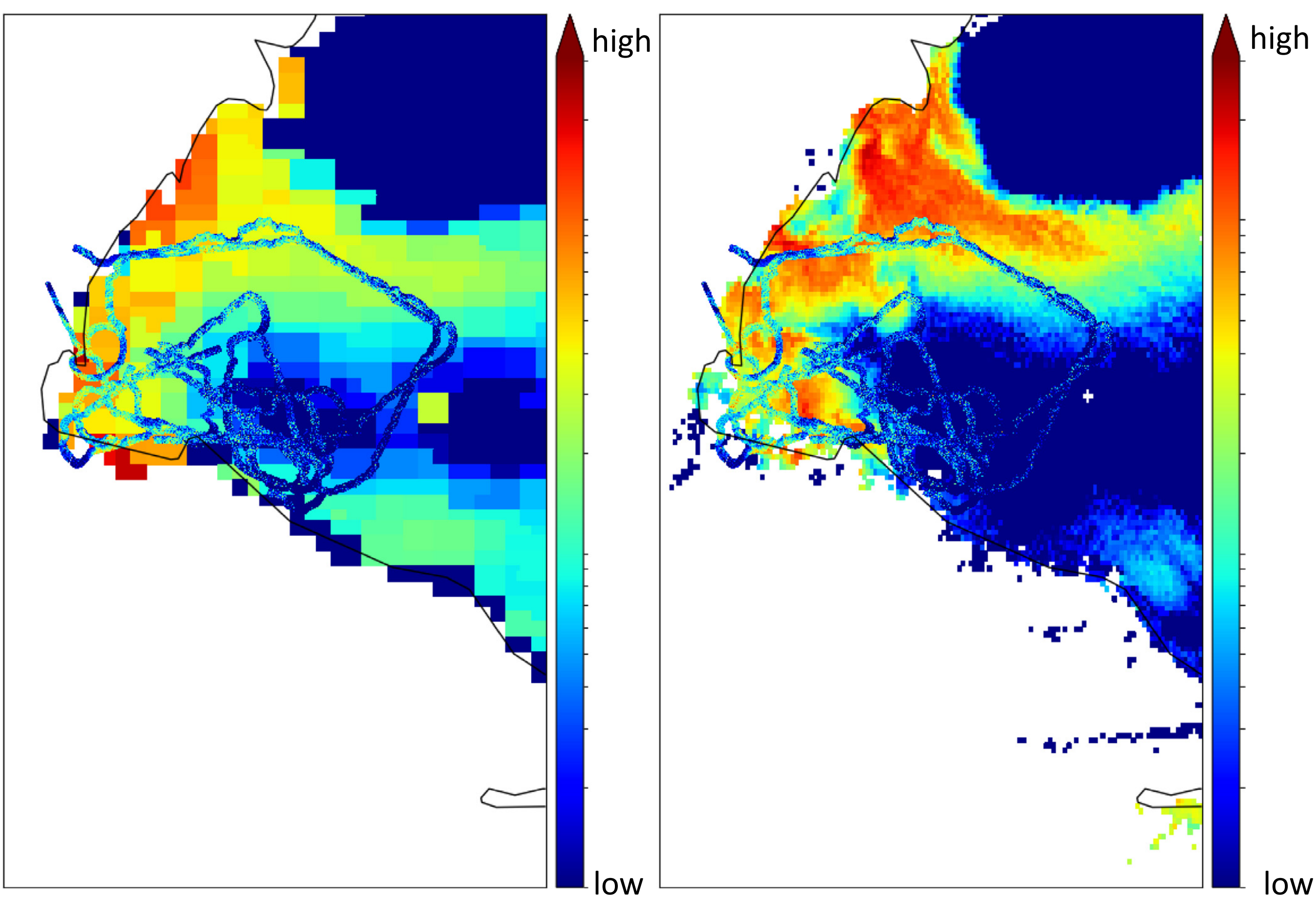

Fig. 2. The cyanobacteria index from low to high, applied to the satellite and hyperspectral imagery. MODIS is on the left and Sentinel-3 OLCI on the right from August 16, 2017. The Resonon Pika II hyperspectral imagery converted to the cyanobacteria index is overlaid on top of the satellite data.

sampling an EXO sonde with identical specifications and calibration protocols as the buoy unit was mounted in a flow cell on the deck with a volume of approximately 80 l. To minimize disturbance to the water being sampled, a streamlined strut was mounted midship on the port side of the boat approximately 20 cm away from the hull with a forward facing intake port 0 .5m under the surface. A flexible impeller pump (Jabsco 11810-0003) attached to the strut pumped water into a diffuser at the bottom of the flow cell and then overboard. The flowrate from the pump while underway was approximately 40 l/min yielding a residence time of approximately 120 s. Vessel speed during underway sampling was approximately 5 m/s giving spatial residence distances approximately 600 m.

Decorrelation scales

A decorrelation scale is the point at which a time series correlated with itself, at a set lag measured in time or space, falls below a predetermined threshold as either the zero crossing or the 95% confidence interval, critical value = 0.361, for $n = 60$, two-tailed from (Zar, 1999)). Decorrelation scales are widely used to determine the scales of variability in biological and physical processes, providing information on how these processes interact and drive ecosystem changes (Abbott and Letelier, 1998; Denman and Abbott, 1994) This method is transferrable to many types of time series from buoys, satellite and hyperspectral data sources and also bio-optical drifters. This has been previously documented on the coast of California, recognizing the change and decrease in the decorrelation scales from onshore to offshore and within upwelling retentive embayments (Vander Woude et al., 2006). Decorrelation time scales have not been applied in the Great Lakes and offer new insight for ecosystem modelers, ship board survey schemes and the time scales that can contribute to bloom development around drinking water intakes along the shorelines of the Great Lakes. Decorrelation scales can also be lagged in space or across pixels, as a time series correlated against itself that is derived from spatial data, in cases where a line is drawn across the satellite or hyperspectral image to form the time series. The same technique was applied in the western basin of Lake Erie and spatial scales of cyanobacteria were explored during the bloom season by comparing satellite HAB bulletin data and the hyperspectral flyovers.

Results

Spatial decorrelation scales from imagery

Satellite and hyperspectral imagery provide a synoptic view compared to moored instrumentation with high-resolution temporal measurements. The spatial variability between satellite (30 m–1 km) and hyperspectral (~1 m) data has inherent differences because of the

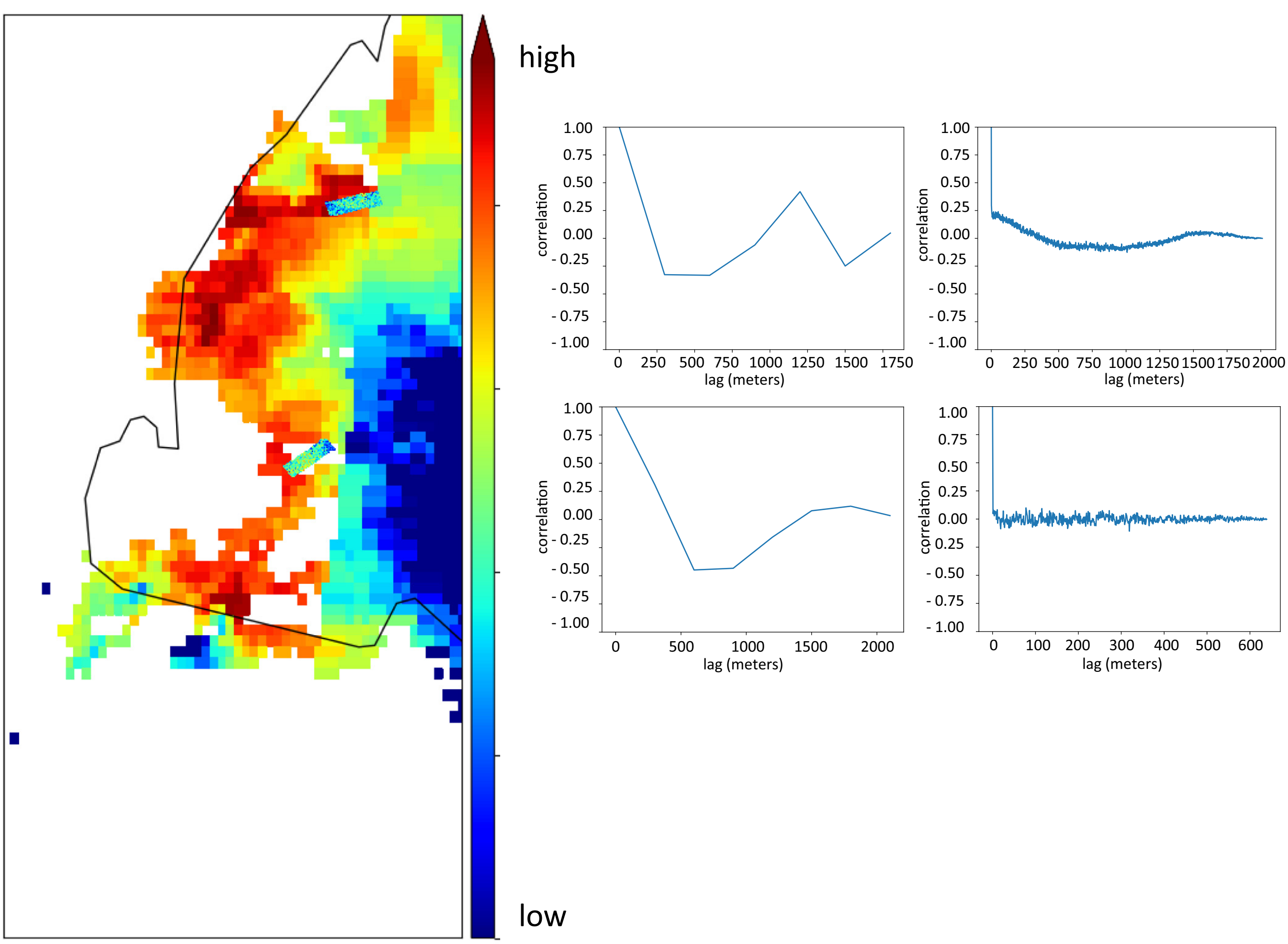

Fig. 3. A close-up version of the western basin of Lake Erie where the Maumee River is located, showing two hyperspectral images to the north and south overlaid onto the Sentinel-3 OLCI image. The spatial decorrelation scale is on the left for the Sentinel-3 OLCI image values taken from the pixels located under the hyperspectral image. The spatial decorrelation scales on the right are from a line drawn down the middle of the hyperspectral image.

spatial resolution or pixel size and the level of detail acquired from one meter resolution hyperspectral images. Binning up to the satellite data resolution is not possible due to swath width differences and resultant directionality of the hyperspectral signal. Fig. 2 illustrates the strong spatial variability in spatial scales in the western basin of Lake Erie showing the overlap in CI values on August 16, 2017 with the hyperspectral imagery flight lines and the MODIS (1 km) and OLCI (300 m) satellite images, respectively. Using only the cyanobacteria index, a line was drawn across an OLCI and Resonon hyperspectral image from August 16, 2017 to create a time series of spatial values within the extent of one Resonon hyperspectral image. Approximately 7 pixels (300 m) fit within the length one Resonon image (Fig. 3). The middle line of the image was extracted from the hyperspectral CI images and the subsequent decorrelation scales were calculated. The spatial decorrelation scale for the satellite image CI values was 300 m, the size of one pixel, and the decorrelation scale for the hyperspectral image was 335 m. In this case, on a day with a prevalent cyanobacteria bloom, the variability was captured from the satellite image in this more northern location of Fig. 2. By choosing a more southern location, in the vicinity of buoy WE2, where the blooms were typically rapidly changing, hyperspectral imagery is more effective, with a decorrelation scale of 8 m compared to the OLCI satellite image (decorrelation scale, 600 m). At a scale of 8 m, this would reflect process such as windrows, Langmuir circulation or edge detection from the Maumee River plume or the harmful algal bloom. The western basin of Lake Erie changes on rapid space and time scales, and hyperspectral imagery is crucial to capturing variability related to surface bloom patchiness and wind-driven mixing events.

Temporal decorrelation and cross correlation scales at the buoys

Temperature is also a key driver in cyanoHABs growth and was also evaluated against the scales of variability for the cyanobacteria. There was a peak in temperature around July 15, 2017 and a peak in

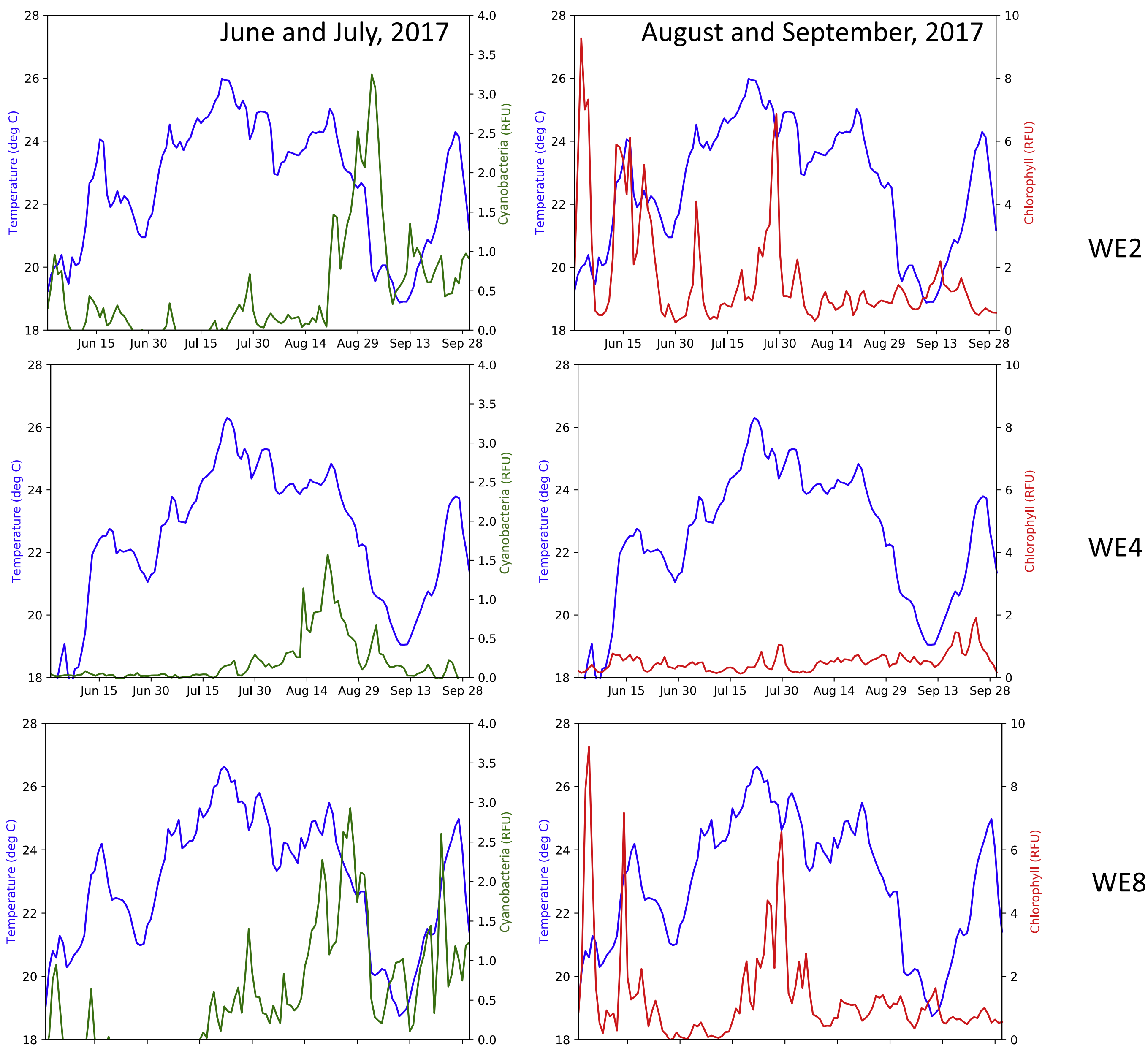

Fig. 4. Time series from June 1 to July 31, 2017 and August 1 to September 31, 207 for buoys WE2, WE4 and WE8. Blue is temperature, red is chlorophyll and green is blue-green algae.

cyanobacteria from the August 15th to August 30th, depending on the buoy location at WE2, WE4 or WE8 (Fig. 4). Chlorophyll peaks earlier in the season at WE2 and WE8. Each of these buoys is situated in a diverse biological and physical environment. The time scales from the decorrelations scale analysis are on a range of 4–13 days for temperature, chlorophyll and cyanobacteria depending on the buoy's location (Fig. 5) and vary from site to site based on the chemical, biological and physical controls at each buoy location. There is an important dissimilarity in the decorrelation scales during the June to July months, cyanobacteria and chlorophyll are closely related with each other with temperature loosely following the same scale. As the time series transitions into August and September, the autocorrelation scales deviate between chlorophyll and cyanobacteria with much shorter time scales for chlorophyll and longer time scales for temperature and cyanobacteria (from 5 to 11 days) during August to September. This directly relates to the cross-correlation scales from each of the buoys for the same time periods (Fig. 6) with temperature leading the cyanobacteria signal. With the greatest interest being cyanobacteria, this time series is autocorrelated with temperature to represent the relationship between biological and physical processes. The maximum correlation of cyanobacteria to temperature is a point of interest to examine how long it takes for these two parameters to reach maximum

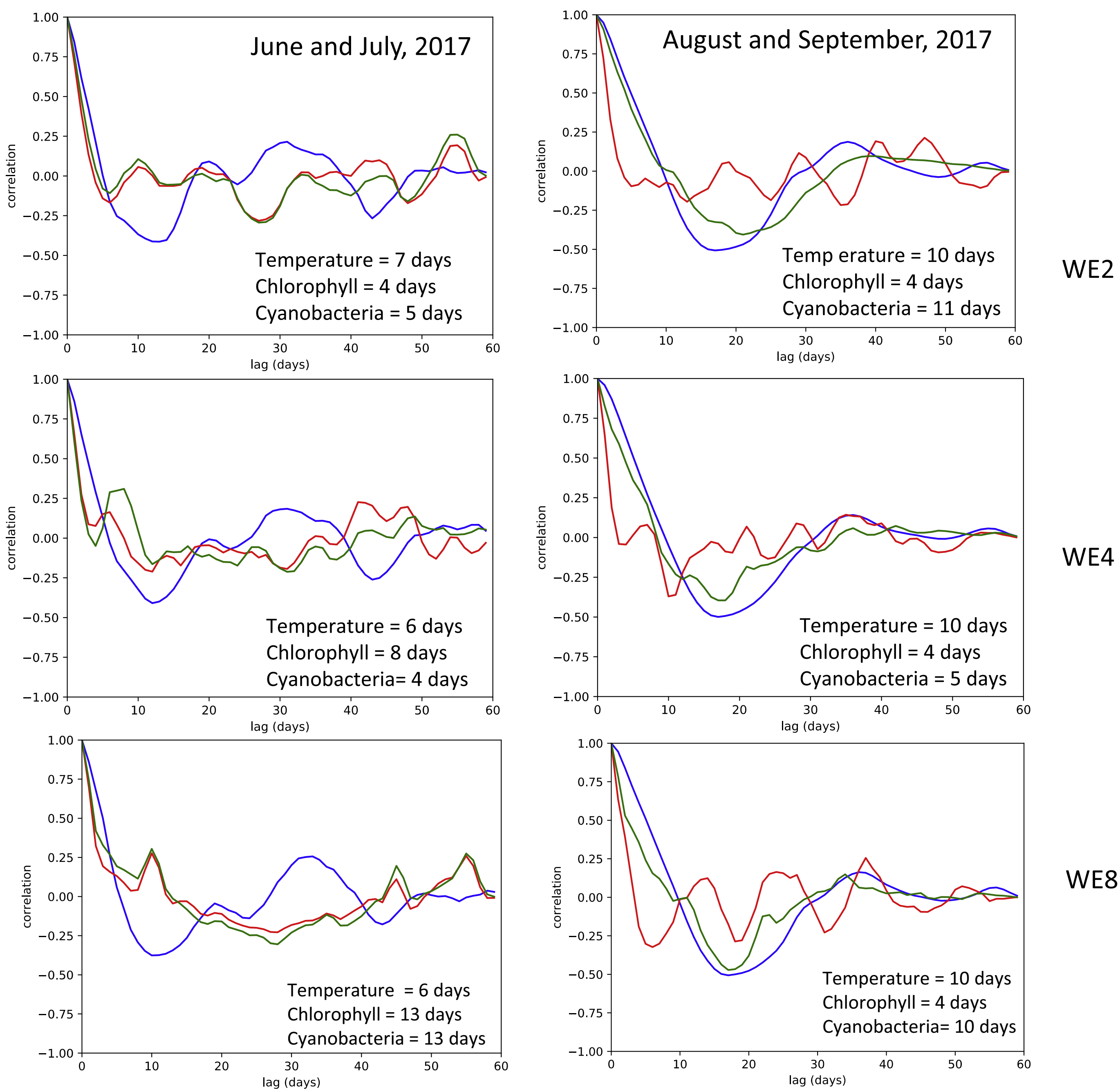

Fig. 5. Autocorrelation scales with decorrelation scales as when the curves reach the 95% confidence interval for June 1 to July 31, 2017 on the left and August 1 to September 31, 2017 on the right. The decorrelation scales are listed in each box for buoys WE2, WE4 and WE8. Temperature (blue), Chlorophyll (red), Blue-green algae (green).

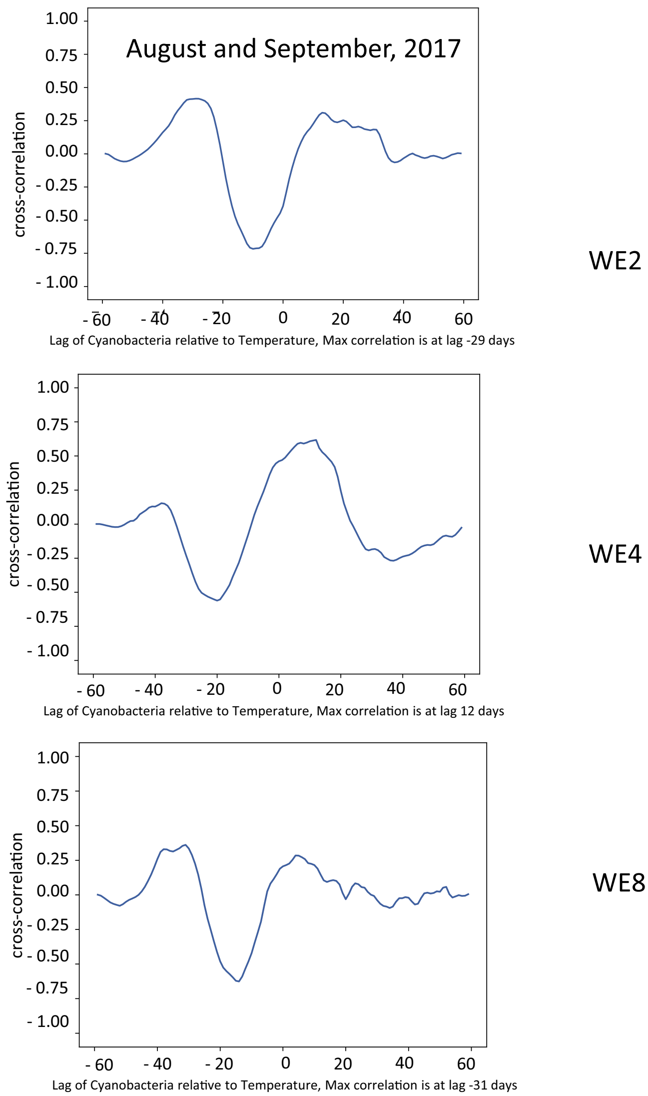

Fig. 6. Cross-correlation scales for blue-green algae versus temperature with the decorrelation scale labeled on the x-axis. This is only for the August–September period.

correlation. The shortest lag at WE4 occurs during both 60-day time series and the longest at WE2. These lags are highly dependent on physical, chemical and biological processes in the vicinity of each buoy.

Spatial and temporal decorrelation scales of shipboard mapping during NOAA alliance for coastal technology survey

During the NOAA Alliance for Coastal Technology Survey on August 16, 2017 the underway sampling system was used to measured temperature, chlorophyll and cyanobacteria. Fig. 7 shows the trajectory of the ship and the cyanobacteria value overlaid onto the CI OLCI satellite image from the same day. The shipboard survey was from 9:46 AM EST until 4:13 PM EST and the discrepancies in the colour shading of the CI values is due to the time the OLCI sensor was overhead at 10:46 AM EST, a snapshot of the total ship transit time. The measurements were continuous through a flow-through system for the shipboard data and even though they spanned at a longer time period than the satellite overpass, the comparison captures the important variability seen in Lake Erie on short time scales. As has been demonstrated, cyanobacteria biomass values can change within a very short period of time. The time series from temperature, chlorophyll and cyanobacteria (Fig. 8) show the fluctuation in the signal over the trajectory of the ship and the calculated decorrelation scales are on the order 4–10 h over the spatial scale. This was a typical diel cycle for this area for the time period being sampled within the western basin on a relatively calm day. These decorrelation scales importantly capture how the bloom can vary closely in terms of temperature (10h) and cyanobacteria (9 h) on similar time and space scales in relation to chlorophyll (4 h) on a shorter time scale. (Fig. 8).

Contribution to the EPA and weekly reports

NOAA GLERL flies over nearshore waters of Ohio and Michigan weekly to provide cyanoHABs observations in the immediate vicinity of water intakes unavailable from satellite imagery. This data was newly published in a bulletin format in 2017 with the true-colour and cyanobacteria index images over each of the water intakes and is provided to the Ohio EPA and water intake managers. In addition to the satellite bulletin data, the hyperspectral imagery is key for nearshore areas where there are concerns about inherent bottom reflectance issues with satellite data. Additionally, airborne hyperspectral data can be obtained by flying underneath clouds where satellite data is not able to detect cyanobacteria features near drinking water intakes. The time scales and spatial variability has been documented over the past 3 years with the capability of the hyperspectral sensor, adding additional information to the HAB tracker (a three dimensional forecasting model).

Discussion

Lake Erie's recurring blooms of cyanobacteria pose potential health risks that impact recreational and commercial users of the lake. Wynne and Stumpf (2015) showed that the frequency maps of biomass over the past 13 years from satellite imagery (MERIS and MODIS) have a strong difference between phosphorous loading from the Maumee versus the Detroit River (labeled on Fig. 1). This leads into the spatial differences seen between the decorrelation scales at the northern site (close to the Detroit River) versus the southern site (by the Maumee River) and the potential increase in spatial variability with lower spatial decorrelation scales by the Maumee River. Wynne et al.(2015) also recognized that blooms were more frequent around the Maumee River discharge area in the western basin, this was also evident with the CI spatial decorrelation scale results where blooms are more likely to be changing at different spatial scales due to nutrient input and physical conditions. The spatial scales, otherwise known as patchiness, variation extends from km to 1-meter streaks that are kms long as seen in the hyperspectral imagery. (https://www.glerl.noaa.gov/res/HABs_and_Hypoxia/airSatelliteMon.html).

In contrast, the temporal scales from the buoy locations show advection of spatial scales past the sensor at the speed of horizontal currents (pers. Mark Rowe). Rowe et al. (2016) also described the vertical migration cyanobacteria that show a regular diel cycle of stratification of blooms during the day to convection at night. To limit this variability, a daily average eliminated this diel cycle to look at time scales of bloom development on a 60-day time series. The 60-day time series of chlorophyll and cyanobacteria buoy data represent the long-term evolution of the cyanobacterial bloom in terms of growth and decay of the phytoplankton over weekly time scales, at the initiation and senesce of the blooms. When decorrelation scales are on the order of 4–13 days for buoys located in the vicinity of the Maumee River where the bloom is more frequent, it becomes apparent that these time scales can be used to understand sampling and surveying plans to best provide early awareness of bloom events for stakeholders. At each of the buoy locations, there was also a significant interaction between the temperature and biological parameters that were best interpreted using the cross-correlation scales of the values. Depending on the proximity to the Maumee River, the cross-correlation peak was between 12 and 29 days for

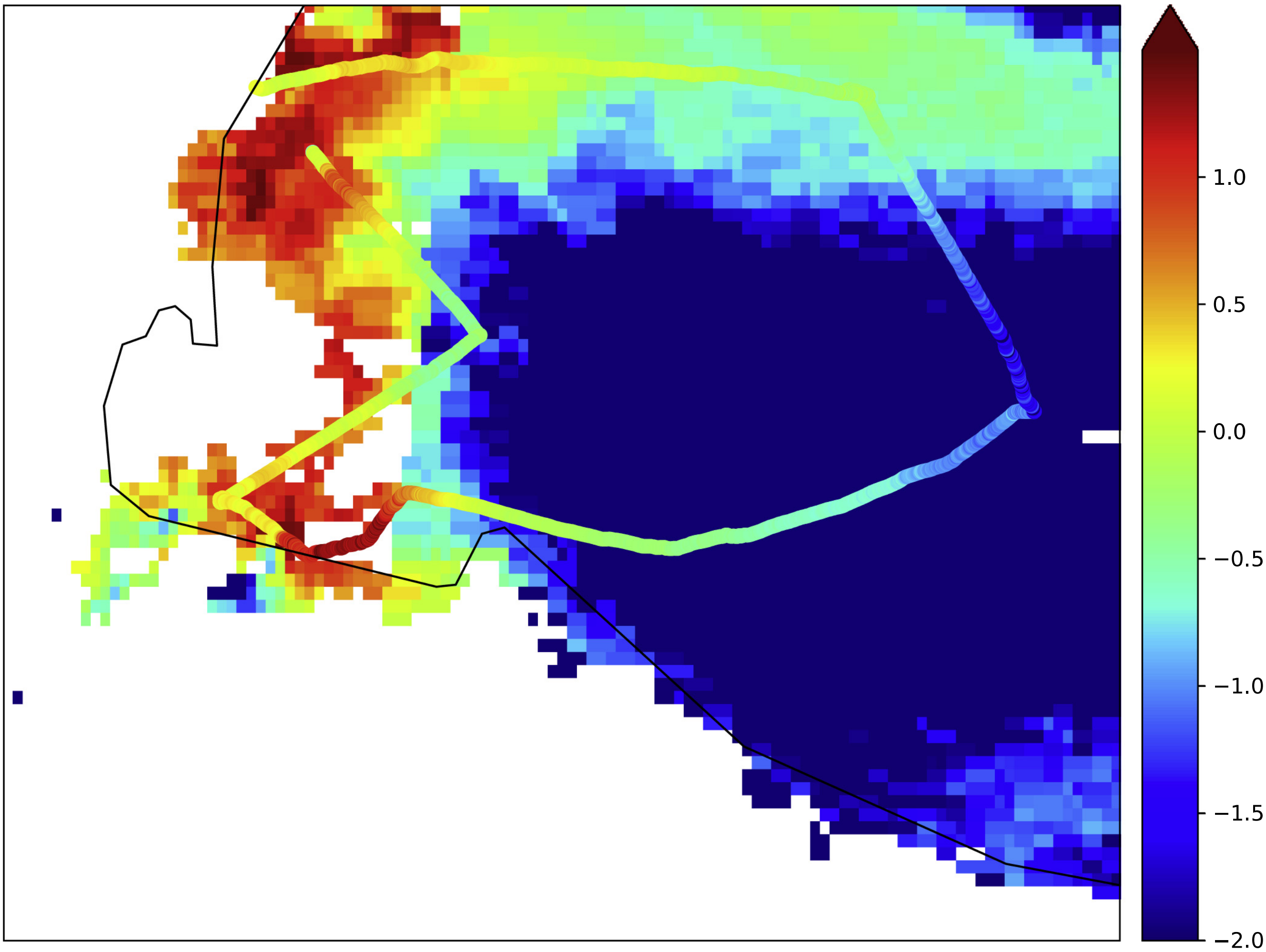

Fig. 7. The EXO blue-green algae data from the shipboard survey overlaid onto the Sentinel-3 OLCI image converted to the cyanobacteria index on August 16, 2017. The colour scale is applied to the cyanobacteria index from low to high.

cyanobacteria and temperature, changing drastically moving northwards towards the Detroit River. The combination of spatial and temporal scales from shipboard mapping adds a third way to analyze the variability in Lake Erie and on hourly time scales. This is crucial information for surveying and early-warning systems to determine the frequency to sample and where to sample. This also solidifies the current weekly sampling over the western basin of Lake Erie with bloom development happening on decorrelation scales of 4–10 for cyanobacteria at each of the buoys analyzed, the hourly information from the buoys that aids in knowing the vertical and horizontal distribution of the blooms (especially in the vicinity of drinking water intakes that are at depth), and the spatial information needed synoptically from both satellite data and hyperspectral data for different spatial scales of variability on meter to km scales.

The next steps and future work under the Great Lakes Restoration Initiative funding through the Environmental Protection Agency are to have synoptic time and spatial scales of variability readily available to municipalities and managers on a weekly basis as part of the product distribution. Decorrelation scales will be calculated for buoys from the previous month and for hyperspectral images over the drinking water intakes that NOAA GLERL flies over every week. This resource is incredibly important to pinpoint and predict the timing synoptically for managers that have limited budgets and are charged with maintaining the safety of drinking water for those surround the Lake Erie western basin.

Conclusion

This analysis from a variety of space-borne, airborne and in-water sensors was an innovative approach to understanding the scales of variability in the western basin of Lake Erie during cyanoHAB events. The goal is to continue to use this network of sensors as a combined effort to aid in the early detection of cyanoHABs, repeatability of reporting how cyanoHABs change in time and space throughout the season, and differences of scales of variability between season. The addition of repeated airborne flyovers of locations in the western basin of Lake Erie (i.e. fly over the buoy locations 4–5 times within a day) will aid in understanding the spatial and temporal scales of variability on an hourly time-scales throughout the season, providing daily timing of the maximum concentration of cyanoHABs at the surface to drinking water intake managers in the vicinity of their water intakes, possible timing of horizontal migration of cyanoHABs and best-sampling practices for scientists on the water.

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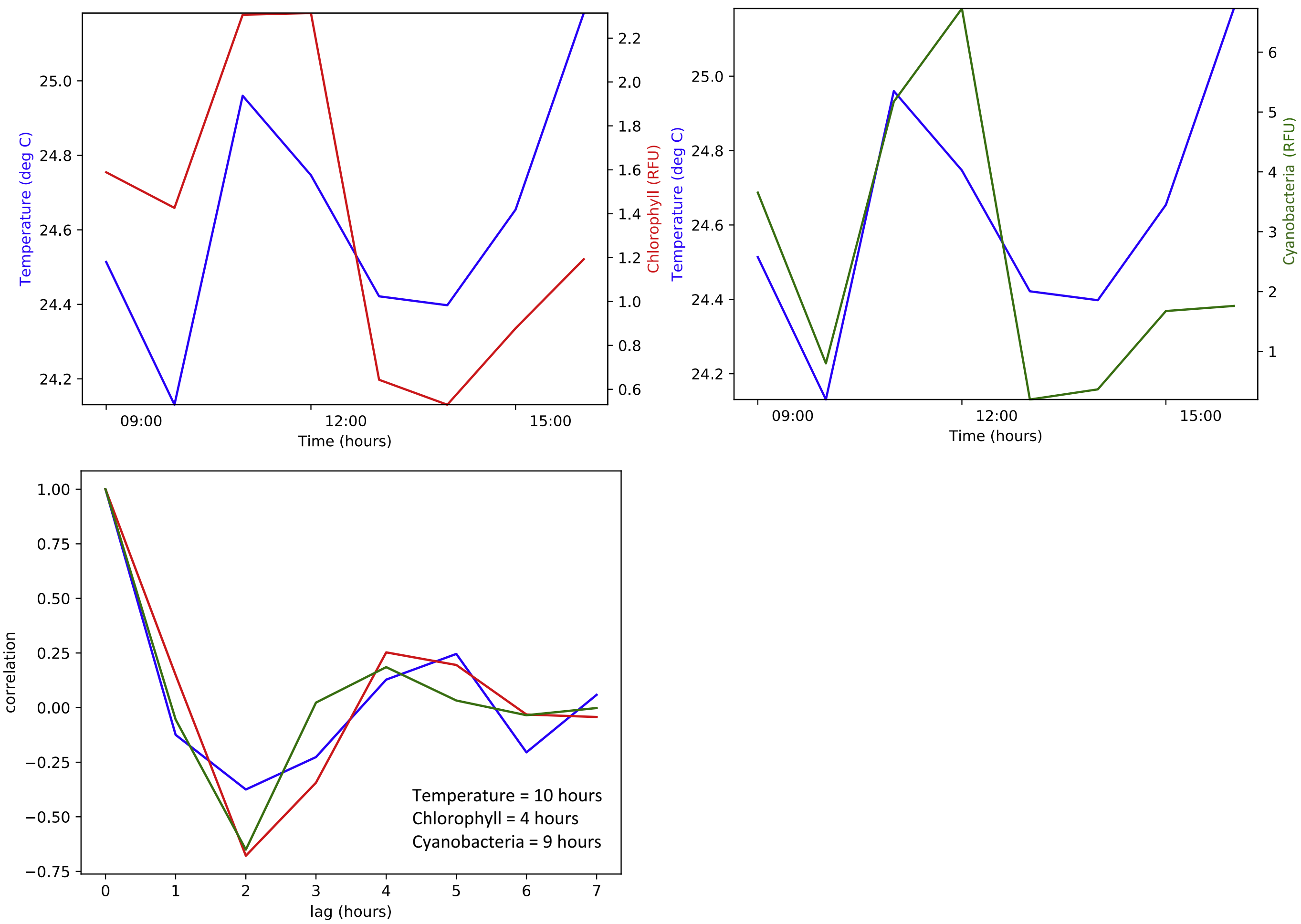

Fig. 8. August 16, 2017, time series for chlorophyll and temperature and blue-green algae and temperature from the EXO sensor along the ship's trajectory on the top two panels. The lower panel shows the autocorrelation result and the decorrelation scales along that trajectory (chlorophyll:red, temperature:blue, blue-green algae:green).

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